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FLIGHT PERFORMANCE RESERVE
FOR
ATLAS/CENTAUR MISSIONS

AY62-0015A

REVISION A

6 April 1964

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FOREWORD

This report documents the results of a study defining the flight performance reserve of typical Atlas/Centaur missions. The study was conducted by General Dynamics/Astronautics under Contract No. NAS3-3232.

The purpose of this report is to provide data showing the propellant reserve required to assure that nominal injection conditions are met with a prescribed success probability. The analysis is based on the root-sum-square technique of combining the effects on payload capability of performance dispersions in various vehicle systems. The results are applicable for both direct ascent and two-burn parking orbit missions.

The data presented herein supersedes the performance reserve data presented in GD/A Report No. AY62-0015, dated 27 July 1962.

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SUMMARY

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The flight performance reserve (FPR) also referred to as propellant reserve, has been determined parametrically for Atlas/Centaur missions. The technique used to determine the FPR was to root-sum-square the effects on payload capability of dispersions in the variables which significantly affect vehicle performance. FPR is presented for standard deviations (one-sigma) of these variables. The three-sigma FPR value which is normally considered in performance calculations is three times the one-sigma value. These data are applicable to both direct ascent and two-burn parking orbit missions.

Author

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SECTION 1

INTRODUCTION

Payload capability is determined by the injection energy required for a mission. For most missions, injection altitude and flight path angle are similar enough to permit the use of injection velocity as a measure of energy. The ideal velocity equation can be used to relate velocity change to vehicle weight as follows:

$$\Delta V_R = \sum_{I=1}^n I g \log \frac{W_1}{W_2} \quad (1)$$

where:

- n = number of vehicles stages
- ΔV_R = total velocity requirement
- I = effective specific impulse
- g = gravitational constant
- W_1 = initial weight during a powered phase
- W_2 = final weight during a powered phase

Flight performance reserve (FPR) is defined as that amount of Centaur stage propellant which is held in reserve to compensate for both Atlas and Centaur non-nominal performance. Flight performance reserve is calculated by determining the Centaur propellant reserve required to assure that the nominal velocity requirements can be satisfied.

If total velocity loss (ΔV_T) due to system deviations is:

$$\Delta V_T = \Delta V_{\text{Atlas}} + \Delta V_{\text{Centaur}} \quad (2)$$

then:

$$FPR = (W_N - W_G) = W_G \left(e^{\frac{\Delta V_T}{I g}} - 1 \right) \quad (3)$$

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where:

W_N = nominal Centaur burnout weight

W_σ = Centaur burnout weight with 3σ system deviations

This assumes that the effects of all the dispersions are corrected in the Centaur stage. The principal advantage of this is that the Atlas and Centaur systems can be considered as a unit and hence the effects of all dispersions can be treated statistically.

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SECTION 2

RESULTS

The results of this study are presented in Figure 1 which shows FPR (one sigma) as a function of payload weight. Normally, payload capability is determined based on a 99.86 percent probability of achieving the required mission velocity. The three-sigma value of FPR is three times the one-sigma value.

In previous reports, FPR has been presented as a function of Centaur total mass ratio and gross weight (i.e., Centaur liftoff weight less insulation panels and nose fairing). In order to provide a convenient means of comparison and to provide data in a form compatible with input to current payload computer programs, the results and associated tables and figures are presented again, in the Appendix, as functions of Centaur mass ratio and gross weight.

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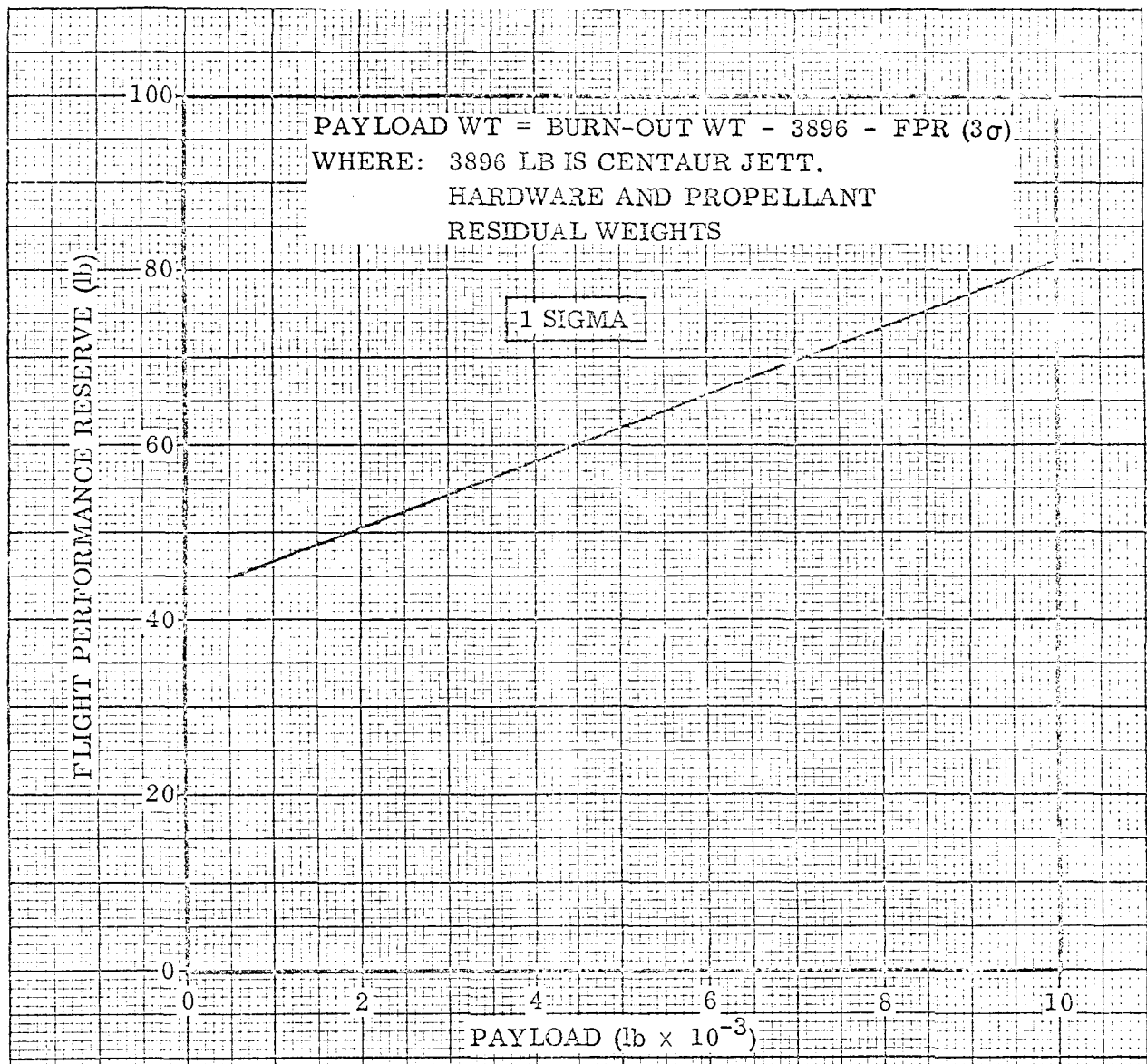


Figure 1. Flight Performance Reserve vs Payload Weight

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SECTION 3

PAYLOAD WEIGHT

Payload weight is defined as nominal Centaur burnout weight less jettison weight (i. e. jettisoned hardware and propellant residuals) and FPR. For this study, Centaur jettisoned hardware and residual weight has been considered constant at 3896 pounds, which corresponds to the operational configuration of Reference 1.

$$W_{PL} = W_{BO} - 3896 - FPR (3\sigma) \quad (4)$$

where

W_{PL} is payload weight

W_{BO} is nominal Centaur burnout weight

3896 is jettisoned weight

Figure 2 shows the statistic probability associated with the nominal and quoted payload weights. The nominal payload is calculated by considering all system parameters to be nominal and therefore corresponds to a 50 percent probability of being achieved. FPR is calculated by assuming three-sigma deviations. Therefore 99.73 percent of the time the payload capability will equal the nominal weight \pm FPR. For 0.135 percent of the time the payload will be greater than this payload range and for 0.135 percent of the time it will be less. Therefore it can be stated that payload capability will equal (or exceed) the quoted payload value with a probability of 99.86 percent (99.73 percent + 0.135 percent).

Payload capability is determined by the type of mission specified. Table 1 shows typical payload weights for the various missions. The lower the payload weight, the lower the FPR requirement since less propellant is required to achieve a required velocity correction.

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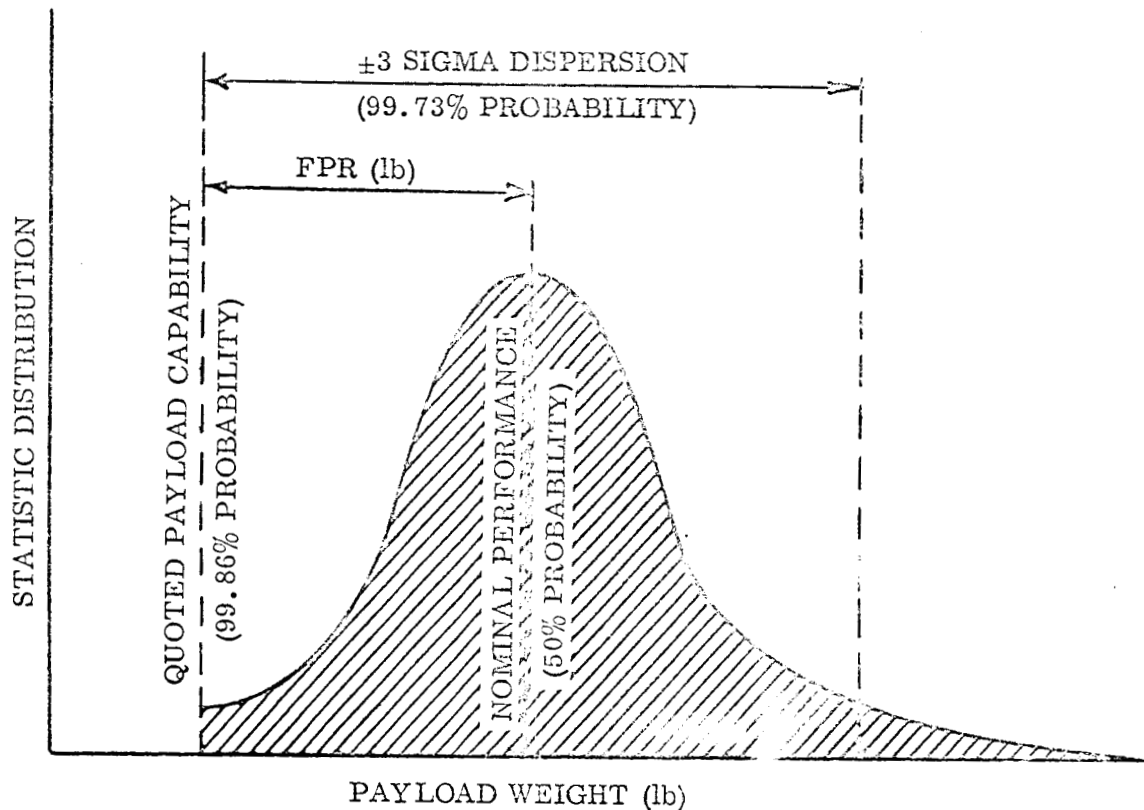


Figure 2. Statistic Probability Associated with the Nominal and Quoted Payload Weights

Table 1. Atlas/Centaur Mission Payload Weights

MISSION	C_3^* (km/sec) ²	TYPICAL PAYLOAD WEIGHT (lb)	FPR (3 SIGMA) (lb)
100 N. Mi Circular Orbit	-61	10,200	246
Escape (Surveyor)	0	2,400	156
Mars	11	1,800	150
Venus	18	1,300	144

* C_3 is twice the total energy per unit mass.

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SECTION 4

PARAMETERS

Twenty-nine parameters such as hardware and residual weights, engine performance, and pitch program are considered in the FPR calculation. Their nominal values and three-sigma dispersions are shown in Table 2.

Table 2. Nominal and Three-Sigma Dispersion of the Parameters

PARAMETER	NOMINAL	DISPERSION (3 σ)
Centaur I_{sp} (system)	Classified	3.53 sec
Centaur PU Residuals	60.0 lb	90.0 lb
Booster I_{sp}	253.6 sec	2.16 sec
Sustainer I_{sp}	215.0 sec	3.09 sec
Sustainer Jett Residuals	1710.0 lb	256.0 lb
Pitch Program	-	5.0 %
Head Wind	-	3.0 σ
Atlas Expendables	248303.0 lb	1889.0 lb
Booster Thrust	330000.0 lb	3615.0 lb
Centaur Jett Residuals	500.0 lb	19.0 lb
Centaur Expendables	30678.0 lb	376.0 lb
Centaur Jett Hardware	3417.0 lb	12.0 lb
Sustainer Thrust	57000.0 lb	975.0 lb
Sustainer Jett Hardware	5548.0 lb	60.0 lb
Hold Down Time	2.35 sec	.2 sec
Booster Jett Residuals	1133.0 lb	98.0 lb
LH ₂ Vented (25 min parking orbit)	70.0 lb	11.0 lb
Booster Jett Hardware	6106.0 lb	30.0 lb
Nose Fairing	1565.0 lb	10.0 lb
Boost Pumps (H ₂ O ₂)	0.1207 lb/sec	0.01 lb/sec

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Table 2. Nominal and Three-Sigma Dispersion of the Parameters, Contd

PARAMETER	NOMINAL	DISPERSION (3σ)
Centaur Venting (Boost)	60.0 lb	9.0 lb
Chill Down Times	5 & 5.0 sec	0.0 sec
Insulation Panels	1000.0 lb	10.0 lb
Centaur Thrust	30000.0 lb	600.0 lb
Centaur Residual GO_2	170.3 lb	8.4 lb
Centaur Residual GH_2	103.8 lb	7.4 lb
Centaur Residual LO_2	68.0 lb	2.0 lb
Centaur Residual LH_2	13.0 lb	1.0 lb
Centaur Tanking Error on Mixture Ratio	5.0	0.06 ($\Delta I_{\text{sp}} =$ 0.25 sec)

SECTION 5

VEHICLE CONFIGURATION

The launch vehicle is a two and one-half stage vehicle composed of an one and one-half stage Atlas and a Centaur upper stage. The nominal configuration characteristics pertinent to this study are described in detail in Reference 1 and summarized in Table 2.

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SECTION 6

MISSION PROFILE

The nominal mission profile is defined by the following phases. A boost phase from liftoff to 5.7 g's acceleration, at which time the booster hardware is jettisoned. The sustainer phase extends from booster engine cutoff to Atlas propellant depletion. During this phase, the Centaur nose fairing and insulation panels are jettisoned. The Centaur stage is ignited subsequent to sustainer engine cutoff and continues until the vehicle is either injected directly into the transfer trajectory (direct ascent) or injected into a 90-n.mi. circular orbit (parking orbit ascent). For the parking orbit ascent, a maximum coast period of 25 minutes is assumed before the Centaur is re-ignited and thrusts until transfer trajectory injection conditions are attained.

SECTION 7

METHOD OF ANALYSIS

Flight performance reserve can be calculated by either 1) repeatedly selecting values for all parameters in a random manner and calculating trajectories until a well defined probability curve, similar to Figure 2, is obtained, or 2) assuming each parameter is independent and calculating one trajectory for each of the dispersed parameters, which is then combined using the root-sum-square method. The FPR obtained for the Mercury/Atlas vehicle using the root-sum-square method has been compared with data obtained by the random selection method (Reference 2) and found to be comparable.

Since energy requirement is the prime item for determining FPR, similar FPR values are obtained for direct ascent and parking orbit ascent trajectories for the same mission. The major difference in FPR due to the ascent modes are the dispersions in parking orbit coast parameters and restart parameters which have little effect on FPR. Only the parking orbit ascent trajectory mode has been considered in this study since it is more convenient to calculate and also gives slightly conservative results when applied to the direct ascent mode.

Trajectories were simulated on an IBM 7090 digital computer from liftoff to parking orbit injection for the nominal and for each incremented parameter. From parking orbit to final burnout, performance was calculated using the theoretical velocity equation which is an excellent approximation since there is negligible velocity loss due to drag, gravity, or thrust misalignment. In this manner, the payload loss associated with each deviation was obtained as a function of payload weight. Table 3 shows the payload loss associated with each parameter (3-sigma deviation) for nominal payload weights of 9375 pounds and 2644 pounds.

The few parameters which result in large payload losses dominate in the determination of FPR. For example, one 100-pound loss is equivalent to sixteen 25-pound losses. Therefore two items are evident. First, the effect on FPR of any small contribution which has not been considered in this study, will be negligible. Second, any attempt to reduce FPR should concentrate on the six or so parameters which contribute 85 percent of the FPR value. An approximate method of determining the change in FPR due to any additional parameter is given below.

$$\Delta \text{FPR} \approx \frac{\Delta X^2}{2 \text{FPR}} \quad (5)$$

where:

ΔX is the Centaur propellant (FPR) required to compensate for a deviation in the parameter.

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Table 3. Effect of Three-Sigma Dispersion on Payload

VARIABLE	PAYLOAD LOSS (LB)	
	(9375 LB PAYLOAD)	(2644 LB PAYLOAD)
Centaur Propellant Residuals	90	90
Centaur I_{sp}	108	92
Booster I_{sp}	104	48
Sustainer I_{sp}	84	45
Sustainer Jett. Residuals	57	28
Pitch Program	69	28
Headwind	53	23
Atlas Expendables	52	23
Booster Thrust	42	21
Centaur Jett. Residuals	19	19
Centaur Expendables	46	23
Centaur Jett. Hdw.	12	12
Sustainer Thrust	22	11
Sustainer Jett. Hdw.	12	6
Centaur Residual GO_2	8	8
Centaur Residual GH_2	7	7
Centaur Tanking Error on Mixture Ratio	7	7
Booster Jett. Residuals	13	7
Holddown Time	8	4
LH_2 Vented (parking orbit)	10	5
Booster Jett. Hdw.	3	2
Nose Fairing	1	1
Boost Pumps (H_2O_2)	4	4
Centaur Venting (boost)	1	0
Chill Down Time	0	0
Insulation Panels	1	0
Centaur Thrust	0	0
Centaur Residual O_2	2	2
Centaur Residual H_2	1	1

Additionally, the change in FPR due to a change in a parameter which has been considered can be assessed by:

$$\Delta \text{FPR} = \frac{Y \Delta Y}{\text{FPR}} \quad (6)$$

where:

Y is parameter's original contribution to FPR

ΔY is change in parameter's contribution to FPR

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SECTION 8

EXCHANGE COEFFICIENTS

Exchange coefficients are partials which relate the effect of a change in a parameter to a change in payload weight. Some parameters have exchange coefficients which have similar variation with payload weight. These are termed linear coefficients and are listed in Table 4 for a 10,200 pound payload. The variation of these exchange coefficients with payload is shown in Figure 3. The exchange coefficients of the remaining parameters are presented in Figures 4 and 5 as a function of payload weight.

Table 4. Linear Exchange Coefficients*

INDEPENDENT VARIABLE	EXCHANGE COEFFICIENT**
Booster Engine Thrust	0.0124 lb/lb
Sustainer Engine Thrust	0.0238 lb/lb
Centaur Engine Thrust	Negligible
Booster Jett Weight (Hardware)	-0.119 lb/lb
Sustainer Jett Weight (Hardware)	-0.212 lb/lb
Nose Fairing	-0.177 lb/lb
Insulation Panels	-0.139 lb/lb
Booster Jett Weight (Trp. Residuals)	-0.145 lb/lb
Sustainer Jett Weight (Trp. Residuals)	-0.236 lb/lb
Centaur Propellant Vented in Boost	-0.078 lb/lb

* The variation with nominal payload is shown in Figure 3.

** The variation in payload weight for a 10,200 lb nominal payload due to a dispersion in the independent variable.

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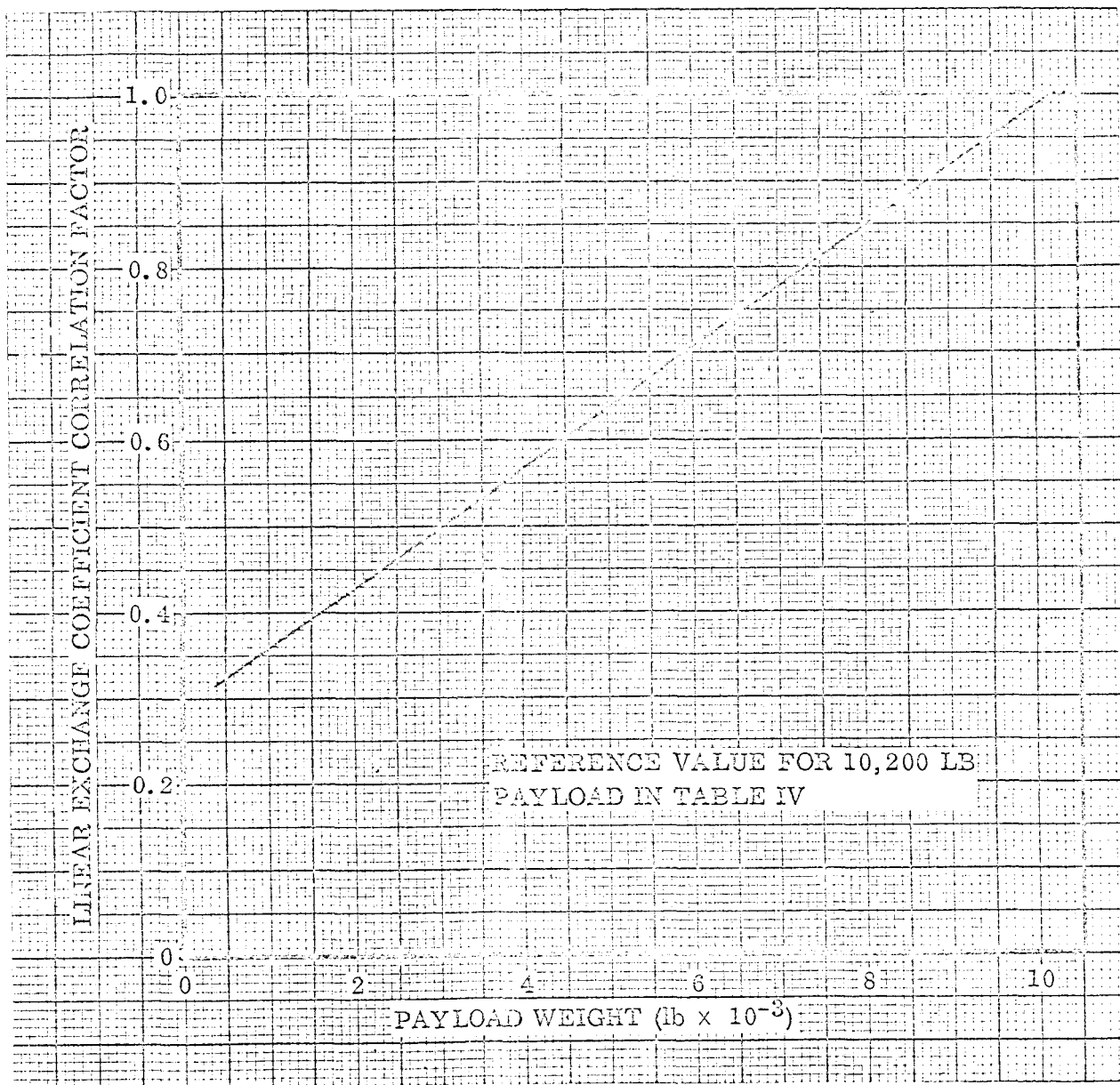


Figure 3. Variation of Linear Exchange Coefficients with Payload Weight

THE VARIATION IN PAYLOAD WEIGHT (W_{PL}) WITH CHANGE IN THE PARAMETER (X)

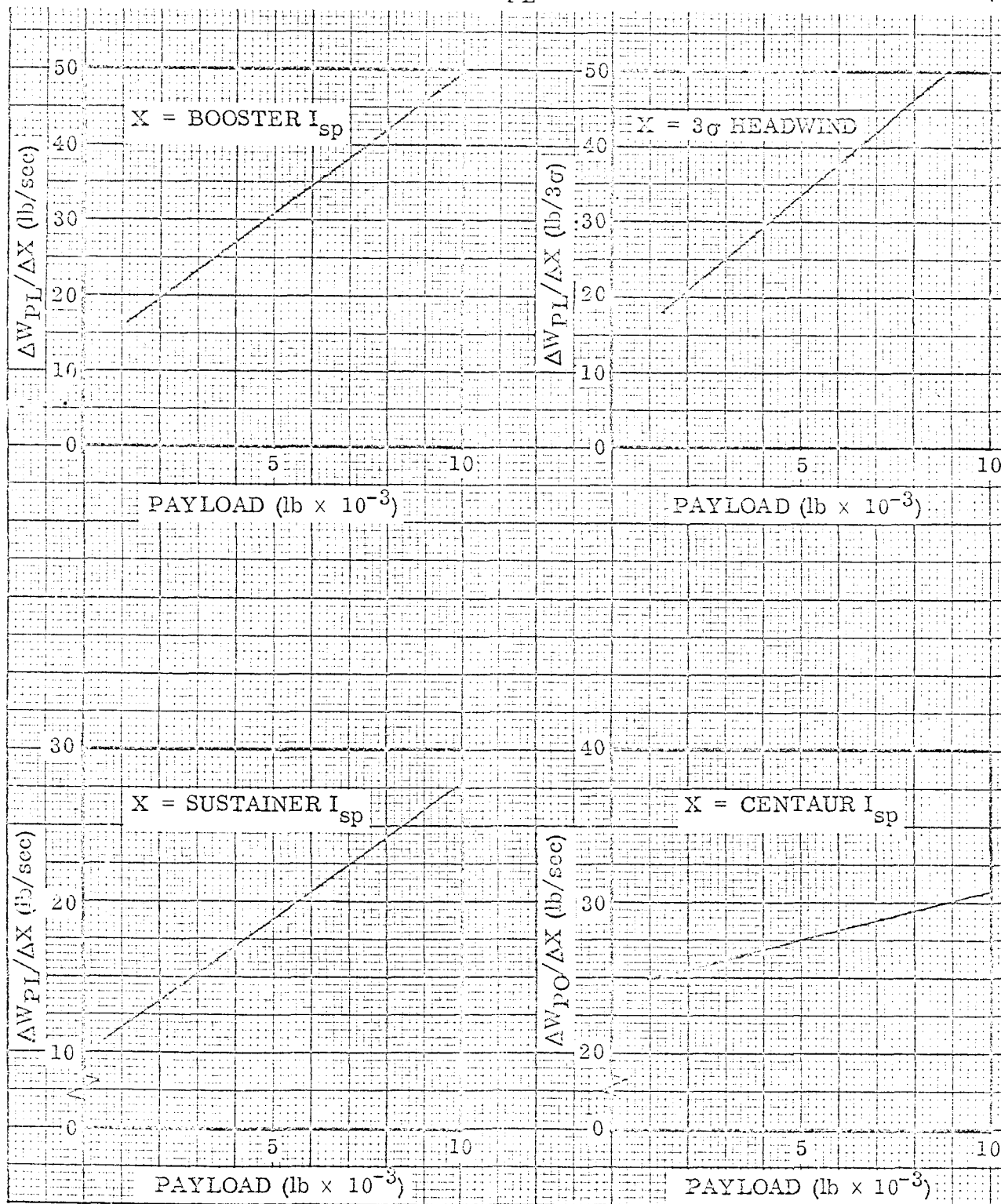


Figure 4. Exchange Coefficients vs Payload Weight

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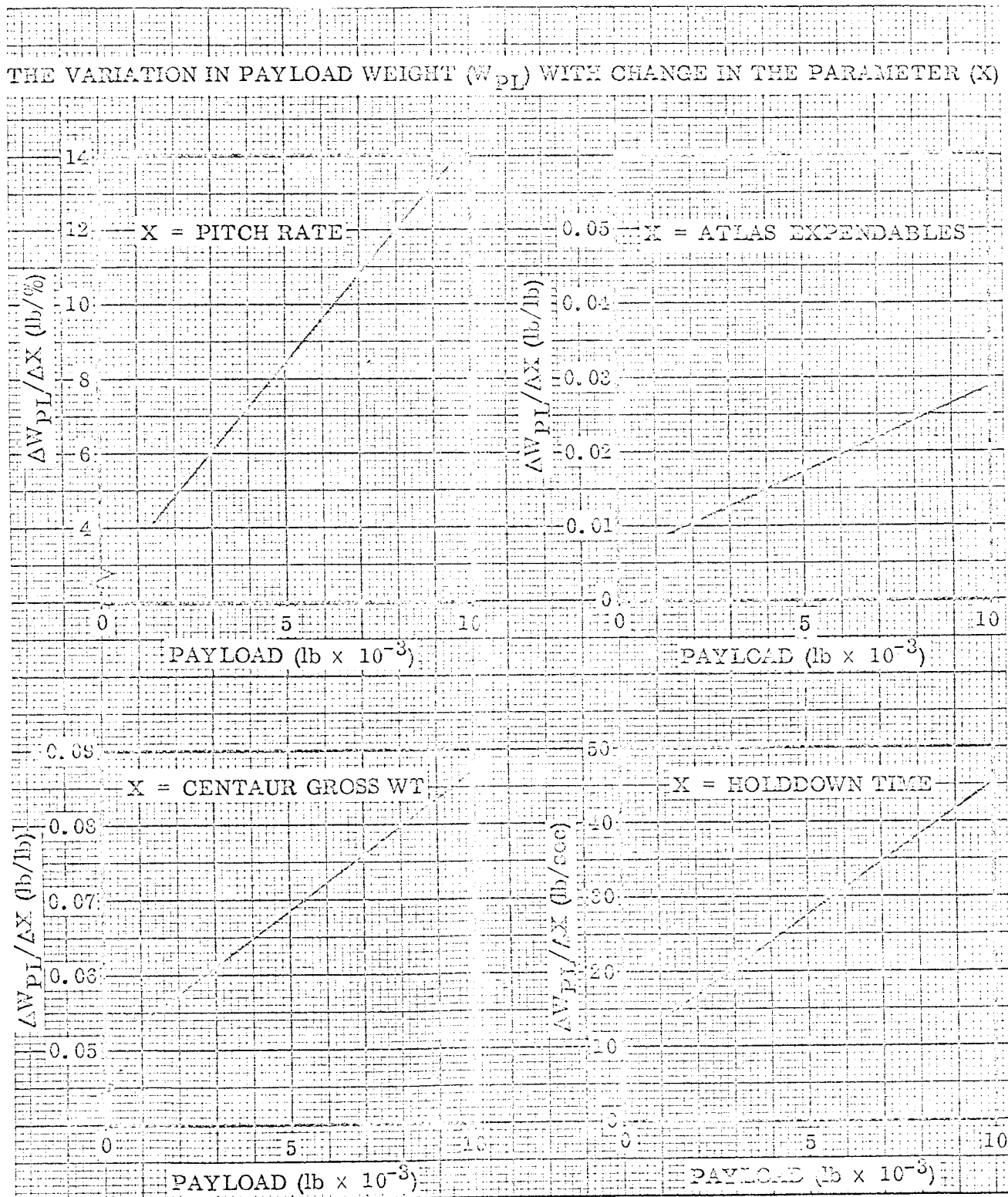


Figure 5. Exchange Coefficients vs Payload Weight

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SECTION 9

REFERENCES

1. General Dynamics/Astronautics, "Monthly Configuration, Performance and Weight Status Report", Report No. GD/A63-0495-4, 21 September 1963, (CONFIDENTIAL)
2. General Dynamics/Astronautics, "Monte Carlo Study of Mercury", Report No. AE61-0853, 15 January 1962, (SECRET)

APPENDIX A

Table A-1. Non-Variant Exchange Coefficients*

INDEPENDENT VARIABLE	EXCHANGE COEFFICIENT**
Booster Engine Thrust	0.0124 lb/lb
Sustainer Engine Thrust	0.0238 lb/lb
Centaur Engine Thrust	Negligible
Booster Jett Weight (Hdw)	-0.119 lb/lb
Sustainer Jett Weight (Hdw)	-0.212 lb/lb
Nose Fairing	-0.177 lb/lb
Insulation Panels	-0.139 lb/lb
Booster Jett Weight (Trp. Residuals)	-0.145 lb/lb
Sustainer Jett Weight (Trp. Residuals)	-0.236 lb/lb
Centaur Propellant Vented in Boost	-0.078 lb/lb

* The variation in weight into a parking orbit due to a dispersion in the independent variable.

** Does not vary with Centaur gross weight (i.e. Payload Weight)

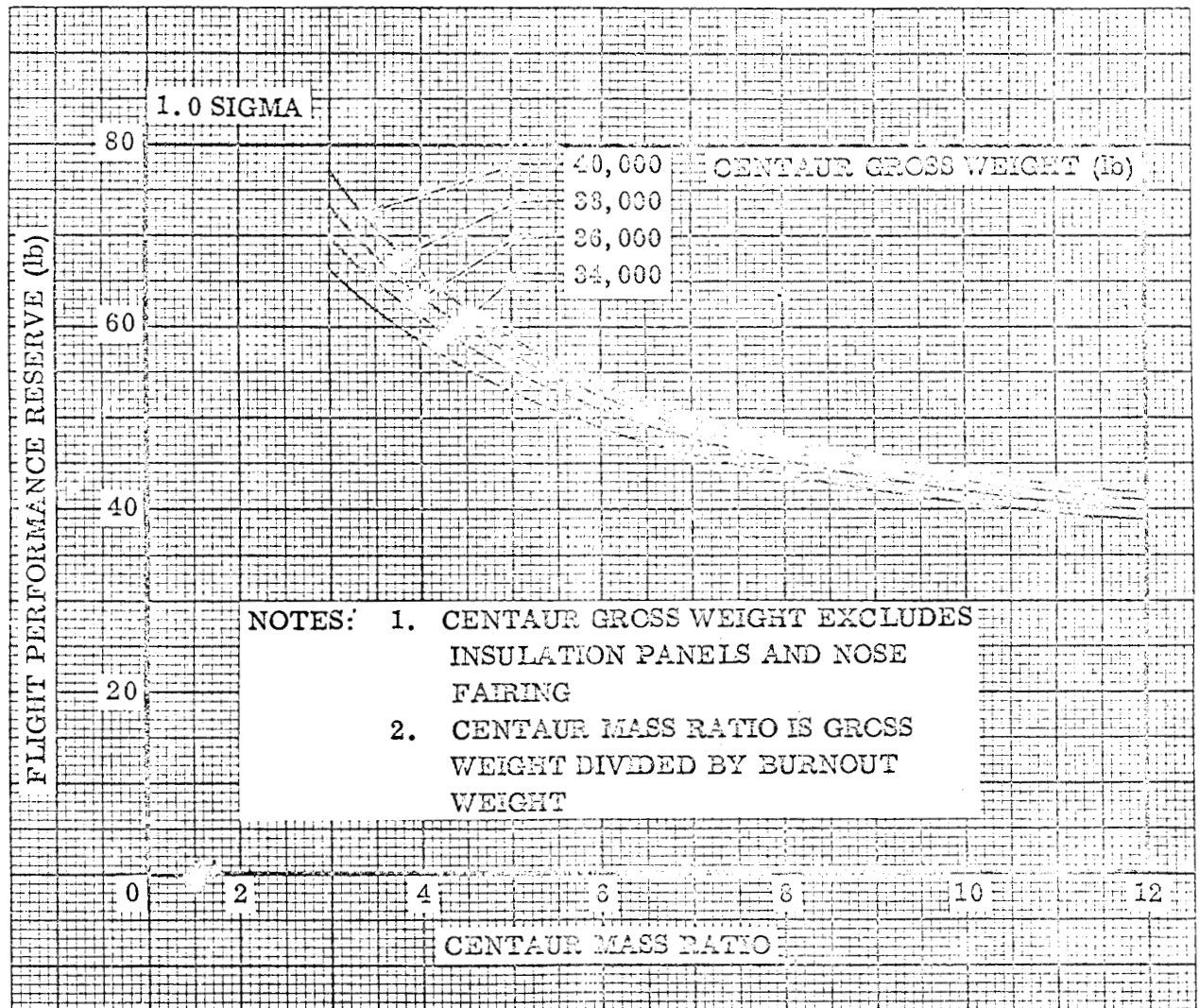


Figure A-1. Flight Performance Reserve vs Centaur Mass Ratio

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THE VARIATION IN PARKING ORBIT WEIGHT (WPO) DUE TO A DISPERSION IN THE
INDEPENDENT VARIABLE (X) VS CENTAUR GROSS WEIGHT

NOTE: CENTAUR GROSS WEIGHT EXCLUDES
INSULATION PANELS AND NOSE
FAIRING

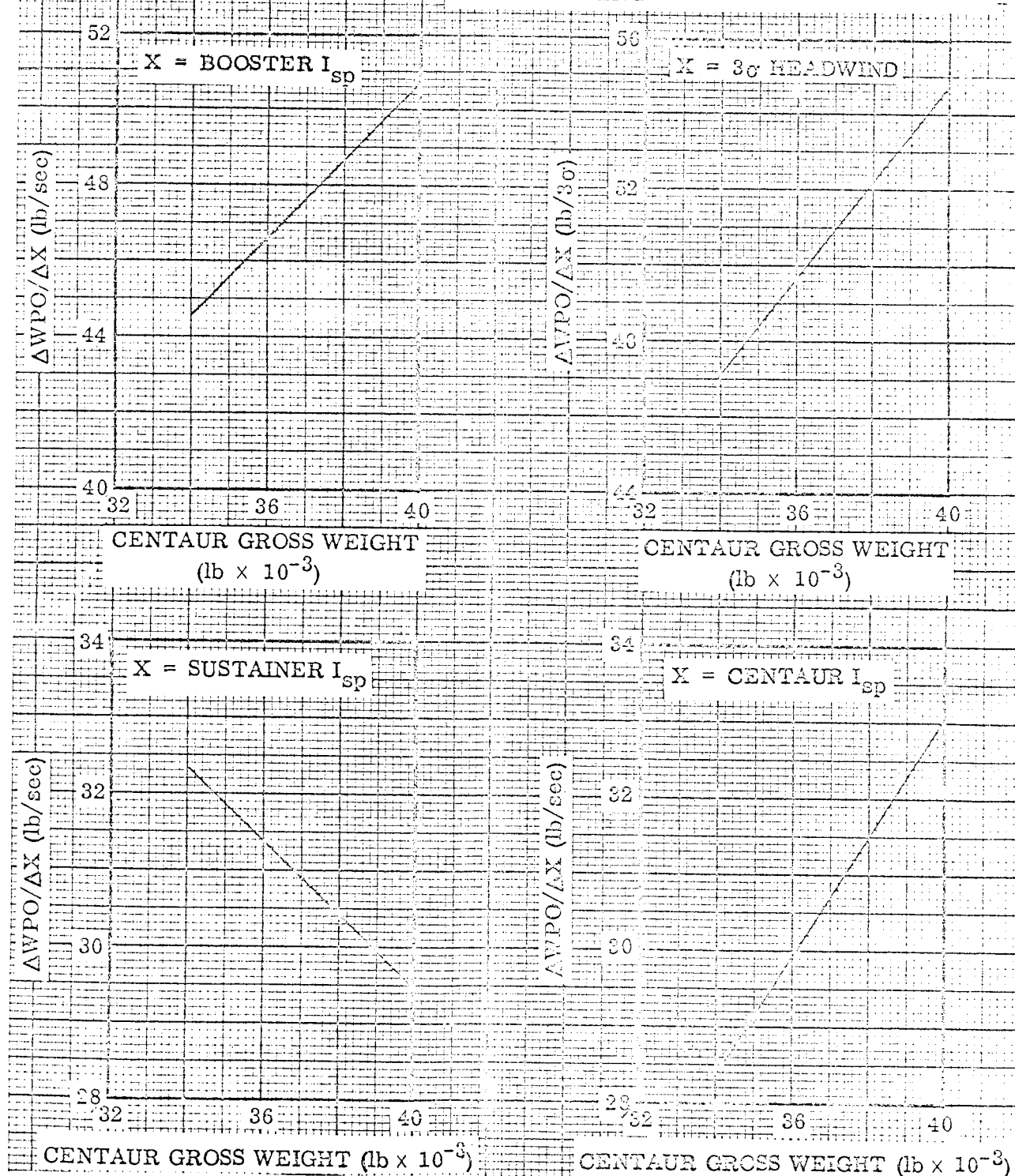


Figure A-2. Variant Exchange Coefficients

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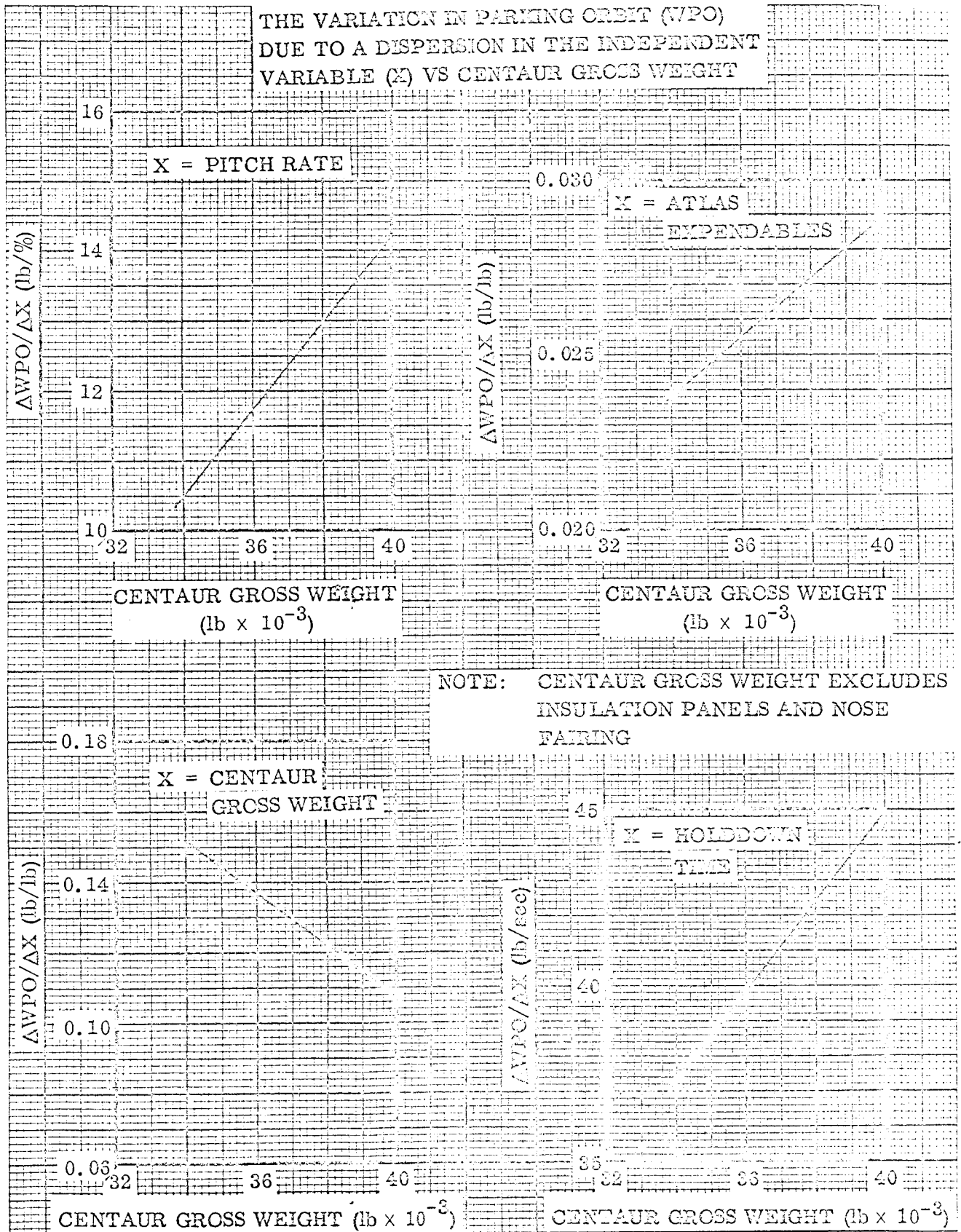


Figure A-3. Variant Exchange Coefficients